FULL SCALE TESTING OF A BRIDGE DECK SLAB REINFORCED WITH CFRP

K. Charleson¹, R. Hutchinson², A. Abdelrahman³, S. Rizkalla⁴ and W. Saltzberg⁵

ABSTRACT
Corrosion of steel reinforcement caused by exposure to chloride environments is considered to be one of the main factors of deterioration of concrete bridges. Fibre reinforced polymer (FRP), offers an effective alternative to the use of conventional steel due to its non-corrosive characteristics. FRP has been used successfully as reinforcement and prestressing material for several concrete highway bridges in Canada, Europe and Japan (Rizkalla and Tadros, 1994. Abdelrahman et al, 1995).

Construction is underway in Headingley, Manitoba for the first bridge in Canada to incorporate carbon fibre reinforced polymer (CFRP) reinforcement into part of the concrete deck slab, shear reinforcements, and for prestressing of four girders. Completion is scheduled for the summer of 1997. This paper discusses a full scale bridge deck model, constructed and tested at the University of Manitoba. The dimensions of the deck are 2950 x 7200 mm. The 200 mm thick deck slab is supported by four precast concrete girders spaced at 1800 mm on centre. The model represents a cut out section from the bridge. The effects of stiffness of the supporting girders and diaphragms have been incorporated into the model to simulate the overall structural response of the slab. Optical fibre sensors as well as conventional electric resistance strain gauges were used to monitor the strain of the CFRP. Behaviour of the deck slab, including the mode of failure under static loading conditions, are presented.

Keywords: bridge, carbon, concrete, deck, FRP, fibre, optic, model, punching, slabs.

INTRODUCTION
Billions of dollars are spent annually on maintenance and repair of concrete highway bridges in Canada. The maintenance and repair budget is extremely high in comparison to the original capital investment of the structure. Most concrete deterioration in bridges can be attributed to corrosion of reinforcing steel due to their exposure to moist chloride environments. Fibre reinforced polymer (FRP) which could be carbon, glass or aramid fibres, provides an effective preventative measure to this problem due to their non-corrosive properties. In addition to their

¹ M.Eng. student, University of Manitoba
² Ph.D. student, University of Manitoba
³ Post-Doctoral Fellow, ISIS Canada Network, University of Manitoba
⁴ President, ISIS Canada Network, Professor of Civil Engineering, University of Manitoba
⁵ Manitoba Highways and Transportation, Bridges and Structures Department
light weight, they are easier to assemble and have a higher tensile strength in comparison to conventional steel reinforcement. FRP reinforcing bars could have a high initial cost, in the order of two to six times more than conventional steel bars (Erki and Rizkalla, 1993). The cost, however recently became more competitive, especially with consideration of the long term benefits in terms of extended service life and associated lower maintenance cost of the structure.

Effective maintenance of concrete highway bridges depends upon the ability to provide regular and comprehensive structural assessments. The use of fibre optic sensors coupled with a remote monitoring system provides a continuous and effective means of assessing structural performance (Rizkalla and Tadros, 1994).

Construction is underway for the first bridge in Canada to incorporate carbon fibre reinforced polymer (CFRP) into sections of the deck slab. The bridge is located in Headingley, Manitoba, Canada. The overall length of the bridge is 165.1 metres and consists of five spans each 32.5 metres as shown schematically in Figure 1. The superstructure consists of 1816 mm deep prestressed "I" girders with a 275 mm concrete deck slab reinforced to act in composite action with the girders. The bridge is designed for a modified HSS 25 (MSS 22.5) vehicle loading as specified by the AASHTO (1994) bridge code. One section of the deck slab will be reinforced with CFRP in replacement of the conventional steel reinforcement as shown in Figure 1. Fibre optic sensors will be attached to the CFRP reinforcements used for both prestressing the girder and reinforcement of the slab to monitor the strains, and therefore providing information about overall structural response.

This paper presents the results of testing a full scale model of the Headingley bridge deck reinforced by CFRP. The model is a continuous slab supported by four girders and tested under a quasi static single concentrated load simulating the wheel load of a truck. The test was conducted at the Construction Research and Development Facility at the University of Manitoba. The strain distribution in the CFRP reinforcement was monitored using optical fibre sensors as well as electrical strain gauges attached to the surface of the reinforcement. Overall response, crack pattern and failure mode of the slab are presented.

DECK SLAB MODEL

The full scale model of the slab was used to simulate the response of the bridge deck slab subjected to a specified design vehicle loading. The model, shown in Figure 2, represents a cut out section of the bridge. The model is supported by four precast concrete beams at 1800 mm centre to centre with steel stirrups extended inside the slab to provide composite action. The model includes two cantilevers of 725 mm clear span. The overall dimensions of the model is 7200 mm x 2950 mm. The slab thickness is 200 mm which is equivalent to the 275 mm slab of the bridge without incorporating the 70 mm wearing surface.

The model is reinforced with 10 mm indented Leadline CFRP bars produced by the Mitsubishi Chemical Corporation of Japan. The bars are made using Dialead coal tar pitch based continuous carbon fibre and an epoxy resin. Material specifications, as published by the manufacturer are
listed in Table 1 (Mitsubishi Chemical Corporation, 1991). The primary reinforcing in the bridge deck slab, which is the bottom reinforcing in the transverse direction, is specified based on the equivalent steel reinforcement ratio specified by the Canadian code (OHBDC, 1991). The area of the CFRP was provided based on modification of the same requirements to account for the lower elastic modulus of FRP compared to steel as follows;

\[ A_{FRP} = 0.003A_g(E_s/E_{FRP}) \]

where \( A_{FRP} \) is the specified area of FRP reinforcement, \( A_g \) is the gross area of the concrete cross section, and \( E_s \) and \( E_{FRP} \) are the moduli of elasticity of steel and FRP respectively. The remaining reinforcement is specified based on the minimum reinforcing requirements of steel which is 0.2 percent in each direction.

Eight fibre optic sensors were attached to the CFRP reinforcement in the central span of the model. Bragg grating fibre laser sensor systems were used to monitor the sensor readings. The sensors were paired with conventional electric resistance strain gauges to confirm the effectiveness of the fibre optic sensors cast in this severe environment. A total of sixty-six conventional strain gauges were attached to the surface of the CFRP bars. Concrete strain of the slab under loading were measured using fourteen Pi-gauges. Lateral and vertical deformation of the entire model were monitored by LMT/LVDT's and dial gauges. Instrumentation is shown in figure 3.

Steel restraint straps were used at the ends of the supporting beams to constrain the lateral movement and to simulate the torsional and lateral stiffness provided by the end and middle diaphragms of the bridge as shown by Figure 2. Finite element analysis was used based on uncracked sections of the slab and beams to design the restraint.

The equivalent wheel load was applied using an 1800 kN capacity, stroke controlled, Enerpac hydraulic jack applied through a 225 x 575 mm steel plate. This simulated the static action of a design vehicle load as specified by the AASHTO Bridge Design Code (1994). The model was tested at the central span under a single concentrated load as shown in Figure 3. A neoprene pad was placed between the steel plate and the concrete slab to simulate the contact surface of the tires of a truck and to avoid local crushing of the concrete. The load was cycled three times at levels of 400 and 600 kN as shown in Figure 5. The slab was unloaded at 600 kN and the end restraints were removed. This was done to simulate two extreme limits of the effect of the bridge diaphragms. The applied load was then cycled three times at load levels of 200, 400, 600 and 800 kN. The slab was loaded to failure.

**TEST RESULTS AND DISCUSSION**

The primary requirement of this experimental program was to verify the suitability of CFRP Leadline as a reinforcement for the Headingley bridge deck slab. The evaluation includes serviceability requirements and ultimate capacity under design and factored loading conditions. The measured ultimate load of the model deck slab was 1000 kN with failure occurring by
punching shear. The specified wheel loading according to AASHTO is 89 kN. The measured load deflection relationship up to failure is shown in Figure 6. The maximum measured strain in the bottom Leadline reinforcement at ultimate was 4 millistrain, compared to an ultimate value of 16 millistrain. Under design load conditions, the maximum measured deflection of the slab with the end restraints was less than 1 mm. This deflection represents a span to deflection ratio of more than 1000. The maximum strain in the Leadline at the design load was 0.4 millistrain.

Crack Pattern and Failure Mode

The crack pattern on the underside of the slab is shown in Figure 7. Cracks were marked during loading before and after the removal of end restraints. The letters R and NR were used to designate the cracks before and after removal of the restraint respectively. During the second 400 kN restraint load cycle, longitudinal cracks were observed extending on each side of the loaded area. Radial cracks were observed at a load level of 600 kN in the presence of the end restraint. Longitudinal cracks projecting in a predominant diagonal direction were observed during the load cycles of 600 and 800 kN after removal of the end restraint. The top surface of the slab was cracked in a rectangular shape running parallel and adjacent to both support girders and extending perpendicular towards the middle of the slab approximately 250 mm on each side of the loaded area. At failure, the top surface of the displaced concrete cone was approximately equal to the loaded area as shown in figure 4. The failure mode of the slab was punching shear. The overall crack pattern on the underside of the slab is described as a hybrid type behaviour which is a combination of flexural and punching shear. Predominant longitudinal cracks and cracks on the top surface of the slab adjacent to the support beams indicates a flexural behaviour mechanism. However, the localized radial cracks at the bottom of the slab as well as the failure of the concrete around the loading plate reflects the punching failure at ultimate.

Load-Deflection

The load deflection relationship with and without end restraint are shown in Figures 8 and 9. The first cracking of the slab occurred at 220 kN in the presence of end restraint. Successive cycles of loading increment caused relatively small or negligible permanent deformations. The behaviour indicates that a considerable loss of the stiffness was caused by removal of the end restraint as displayed by the decrease of the slope of the load deflection curves after removal of the end restraint. This behaviour is also shown in Figure 10 by the increase of the rotation of the supporting girders after removal of the end restraint.

Strain Distribution

Strain in the bottom main reinforcement of the slab within the tested span is shown by Figure 11 before and after removal of the end restraint. The figure indicates that the strain of the main CFRP reinforcement increased significantly with the removal of the end restraint while the strain adjacent to the support girder was unaffected. The maximum observed tensile strain in the reinforcement is 4 millistrain. The strains in the top CFRP reinforcement in the main direction also increased with removal of the end restraint straps and the maximum observed strain was 2.2 millistrain. Figures 12 and 13 show the distribution of strain in the concrete and FRP reinforcing
in the longitudinal direction. These strains are measured at the mid span using P1 gauges and strain gauges respectively. It can be seen that strains show consistency with classical bending theory.

Performance of Optical Fibre Gauges

Optical fibre gauges mounted on CFRP reinforcing bars in the model performed very well through the test. All gauges provided stable readings through load cycling and up until failure. Strain readings of one of the optical fibre gauges positioned immediately under the loaded area and a conventional electric resistance strain gauge located adjacent is shown in Figure 14. The comparison shows an excellent correlation.

Prediction of Ultimate Load Capacity

Predictions for ultimate load were made based on punching shear equations from CSA (1994), ACI (1995), OHBDC and a model developed by Newhook and Mufti (1995). The predictions are shown in Figure 15. The measured load of 1000 kN indicates that the CSA code provides a very good prediction despite the fact that the code equation is for slabs reinforced by steel. The ACI and OHBDC code equations provide a conservative result. The model by Newhook and Mufti accounts for compressive membrane forces developed by lateral girder restraint and provides an unconservative result.

CONCLUSION

Based on testing of a full scale model of a concrete bridge deck reinforced by CFRP, the following conclusions can be drawn:

1. An ultimate load of 1000 kN was sustained by the model compared to an unfactored static design load of 89 kN as specified by the AASHTO bridge design code. This represents an acceptable level of safety.

2. The model displayed satisfactory performance in terms of serviceability requirements. The deflection and strains were very small at the service load limit.

3. Optical fibre sensors mounted on the CFRP bars within the model showed very good correlation with conventional electrical resistance strain gauges indicating satisfactory performance.

4. The predicted failure load based on the CSA code is satisfactory.

ACKNOWLEDGEMENTS

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REFERENCES


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Table 1: Typical Properties for Leadline Reinforcing Bars

<table>
<thead>
<tr>
<th>Diameter</th>
<th>10 mm</th>
<th>Young’s Modulus</th>
<th>147 GPa</th>
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<tr>
<td>Cross Sectional Area</td>
<td>71.8 mm²</td>
<td>Elongation</td>
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<td>Matrix</td>
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<td>Unit Weight</td>
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<td>Fibre Volume Fraction</td>
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<td>Specific Gravity</td>
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<td>Guaranteed Strength</td>
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<tr>
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<td>Thermal Expansion (longitudinal Direction)</td>
<td>0.7x10⁻⁶/°C</td>
</tr>
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</table>
Figure 1: Headingley Bridge

Figure 2: Model Bridge Deck
Figure 3: Experimental Test Set-up

Figure 4: Top Surface of Displaced Concrete Cone
Figure 5: Cyclic Loading Pattern for Test

Figure 6: Measured Load-Deflection Relationship of the slab at mid-span

Figure 7: Crack Pattern at Failure (slab underside)
Figure 8: Load Deflection Curve - Restraint

Figure 9: Load Deflection Curve - No Restraint

Figure 10: Girder Rotation Before and After Removal of End Restraint
Figure 11: Strain of the Main CFRP Reinforcement at Mid-Span

Figure 12: Compressive Concrete Strain at the Top Fibre Measured at Mid-Span

Figure 13: Tensile Strain of the Bottom CFRP Measured at Mid-Span
Figure 14: Comparison of Response of Fibre Optic and Conventional Strain Gauges

Figure 15: Deck Slab Failure Load Predictions